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Title: NorthStar Helium Cooling System Final Report on LANL Contribution

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Los Alamos
NATIONAL LABORATORY

NorthStar Helium Cooling System

Final Report on LANL Contribution

Keith Woloshun and Eric Olivas

4/4/2022

Introduction

From the beginning of NNSA support to the NorthStar development of a production facility for the medical isotope Molybdenum-99 (Mo99), LANL has been responsible for the design and testing of a target and its cooling. The target is comprised of a stack of Mo100 disks separated by coolant flow gaps between the disks and between the first disk and a housing window, which separates the target and its coolant from the vacuum of the beam line. The target, and therefore its cooling requirements, evolved steadily over the years of system development

Water Cooling Test

The initial cooling fluid chosen was water. Several tests were done in 2010. The target is shown in Figure 1. The design was graded disk thickness with thin, 1mm, disks at the front, with increasing thickness toward the back as the beam strength was attenuated. At that time, the target diameter was 12 mm with a 6 mm FWHM beam. With water, cooling was effective but corrosion was excessive. No other liquid coolant can match the heat transfer effectiveness of water other than liquid metals. All other liquid coolant options, also with the exception of liquid metals, would experience the similar molecular disintegration and formation of corrosion promoting ionized particles or free radicals.

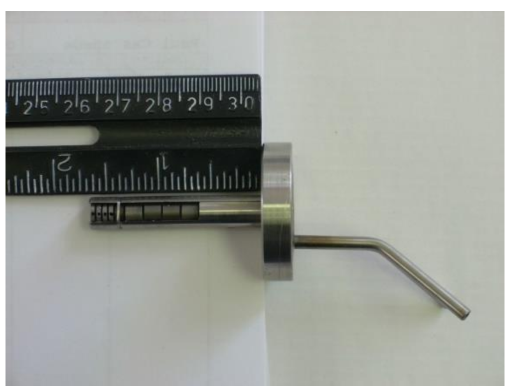

Figure 1. Water cooled target, used in ANL in-beam experiments

First Helium Cooling Test

As water was determined unacceptable because of rapid corrosion the best alternative was gas cooling, and by far the best gas for effective heat transfer is helium, excluding hydrogen for the obvious reason. A roots blower was used for closed loop circulation of the helium but prior to the development and fabrication of such a system and early open loop test was performed in 2011 in the electron beam at ANL.

Figure 2 shows the target holder and the target, with 4 imbedded thermocouples, one in each of the 4 disks. 20 bottles of helium were used in this once-through experiment (Figure 3).

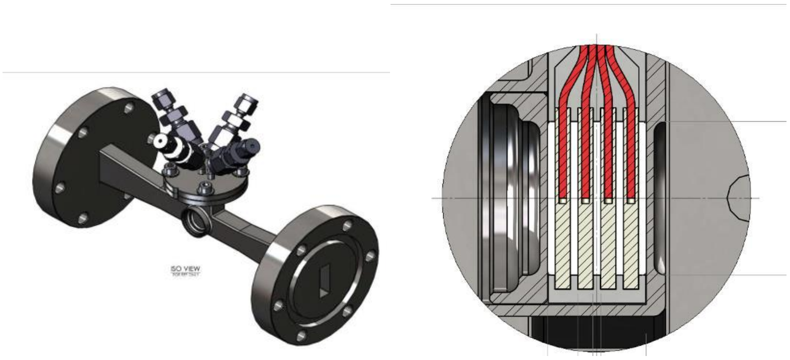

Figure 2. The target housing and target cross section view showing imbedded thermocouple.

Figure 3. Helium was provided to the experiment via 20 full size bottles of helium

The test was done at 17 MeV. Beam power was up to 10.3 kW. Helium velocity in the channels was 197 m/s, heat flux peak of 800 W/cm^2. This test indicated that the heat flux goal of 1000 W/cm^2 was achievable.

Mark I Circulating Helium Loop

To optimize cooling with helium, the density and velocity, Reynold's Number, has to be as high as practically achievable. Density is raised by increasing pressure, but the target must operate in a beam line held at high vacuum, and the beam is heating the target window as well as the Mo100 target. The window is the portion of the target enclosure, or housing, that the beam penetrates. The heating of the window is volumetric, so it is important to keep it as thin as possible to minimize volume. This requires careful design balance between keeping the window heating down with a thin window while maintaining enough strength to withstand the pressure load imposed on the target side. Heat transfer analysis led to the decision to operate at 300 psia gas pressure. At that time, with disks 12 mm in diameter, disks were 1 mm thick and the coolant gaps between disks was 0.5 mm. Numerical analysis led to a required mass flow rate of 100 g/s.

Standalone blowers designed with enclosures sufficient to handle the 300 psi internal pressure were costly: $300 K to $500 K. While this is the ideal method of achieving the pressure conditions the budget was not sufficient. A method of using a low pressure roots blower mounted in a pressure vessel was borrowed from Princeton [1].

The blower selected is Tuthill 3206 PD Plus. The performance specifications are shown in Figure 4. The blower mounted inside the pressure vessel is shown in Figure 5. The blower is driven by a 40 HP motor in spite of the lower HP needed as per the spec sheet but was conservatively used based on Princeton system sizing. The pressure vessel consists of a flange mounted on a base plate and the enclosure, known as the bell, sliding on rails to expose the blower and motor as needed.

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Tuthill

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Date: 3/25/2011

Factory Offices
Tuthill Vacuum & Blower Systems
4840 West Kearney Street
Springfield Missouri 65803-8702 USA
Tel: (800) 825-6937
Fax: (417) 865-2950
blowerxpert@tuthill.com

Application Summary - (New Project: Normal Condition)

Reference/Quote:

AMBIENT CONDITIONS:

Atmospheric Pressure:	14.70 PSIA
Elevation:	0 Feet
Ambient Temperature:	70.0 Fahrenheit

APPLICATION REQUIREMENTS:

Gas Properties:

Gas:	HELIUM	
Molecular Weight:	4.003	
Cp:	1.24 BTU/lb-R	
K Value:	1.665	
Inlet Temperature:	40.0 Celsius	
Inlet Volume Flow:	113 ICFM	
Standard Volume Flow:	2169.6 SCFM	
Mass Flow:	612.00 kg/h	170g/S (220@ 3600 RPM)
Inlet Pressure:	300.00 PSIA	
Discharge Pressure:	320.00 PSIA	

MODEL SELECTED FOR THE APPLICATION:

Model Number:	3206-54T2-X PD Plus	
Materials of Construction:	Standard / Iron	
Flow Direction:	Horizontal Flow	
Connection Size:	2.5 NPT Inlet, 2.5 NPT Discharge	
Seal Type:	Mechanical	
Lubrication:	External Pressure	
Rotative Speed:	2810 RPM (70% of Max)	
Gear Tip Velocity:	2391 FPM	
Discharge Temperature:	127.5 Fahrenheit	53°C
Discharge Volume Flow:	110 DCFM	
Required Input Power:	17.0 BHP	21.8 BHP @ 3600 RPM assuming same inefficiencies
Estimated Blower Noise:	95 dB(A) at 1 meter, open field	
Noise Level Based On:	Fully piped, no silencers	

SELECTED BLOWER OPTIONS:
None

TESTING:
Standard Mechanical Integrity Test
Hydrostatic test, non-witnessed (150 PSIG)
High pressure sealing arrangement
High pressure seal leakage test, non-witnessed
Initial Fill of PneuLube Oil, ISO 100 (8 Gals.)

BLOWER OPERATES OUTSIDE NORMAL DESIGN PARAMETERS. FACTORY APPROVAL IS REQUIRED

Figure 4. Blower performance specs.

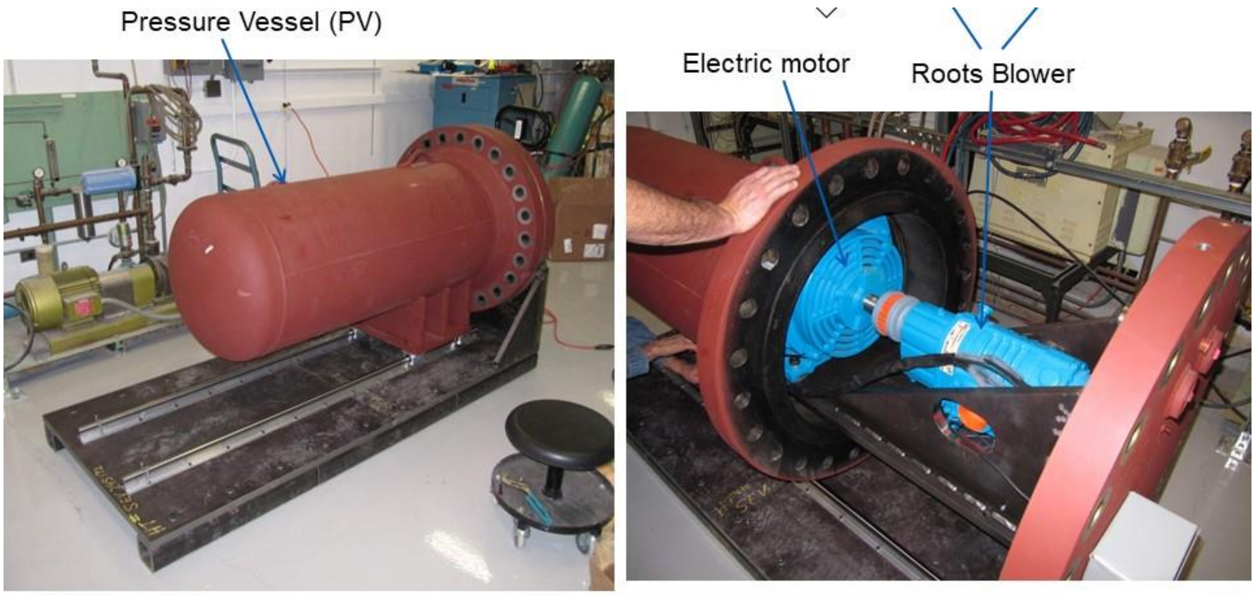

Figure 5. Blower and pressure vessel.

The first blower system procured was set up and operated at ANL for in beam experiments. The layout of the helium loop is shown in Figure 6. The flow meter is a Coriolis type, the heat exchangers are shell and tube type. The filter is a coalescing type for removal of oil vapors. The first test with this system was the cooling of a target with 25 disks 12 mm in diameter. In this test, conducted in 2012, helium velocity of 280 m/s was achieved. This blower performance was as expected. This He loop is still in operation at ANL after 9 years.

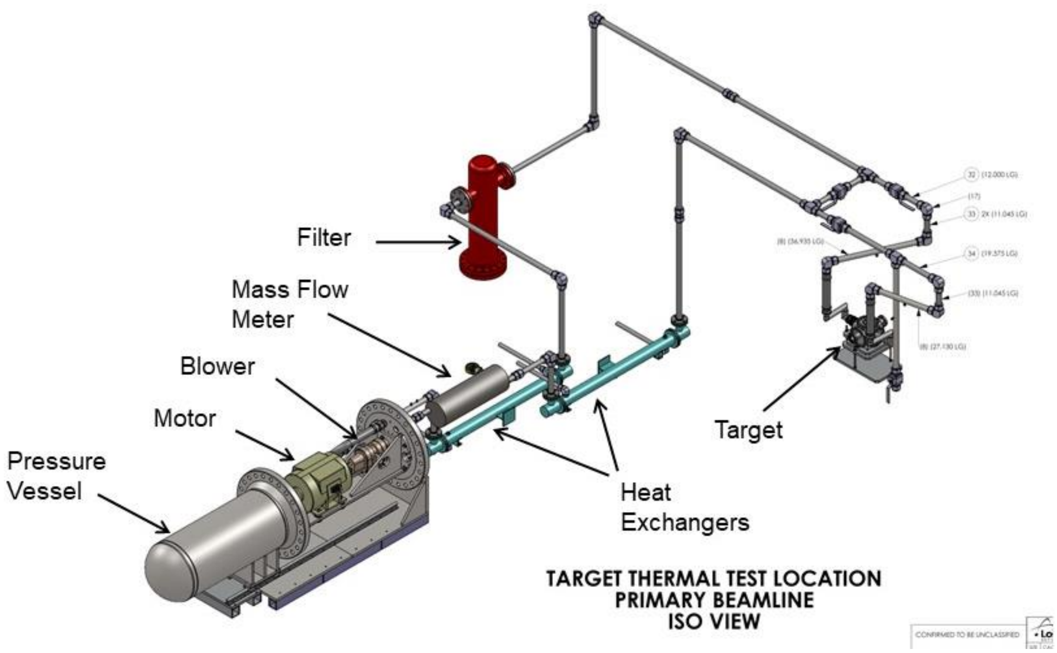

Figure 6. Helium flow loop as implemented at ANL.

An identical blower and pressure vessel system was set up at LANL for out of beam tests. The blower is shown in Figure 7 and the system P&ID is shown in Figure 8. A vortex flow meter was used, but later a paddle wheel type flow meter replaced the vortex type. This was shown to be more accurate, and also cheaper. The heat exchanger is now a plate type.

Figure 7. Blower and motor in the pressure vessel, LANL loop.

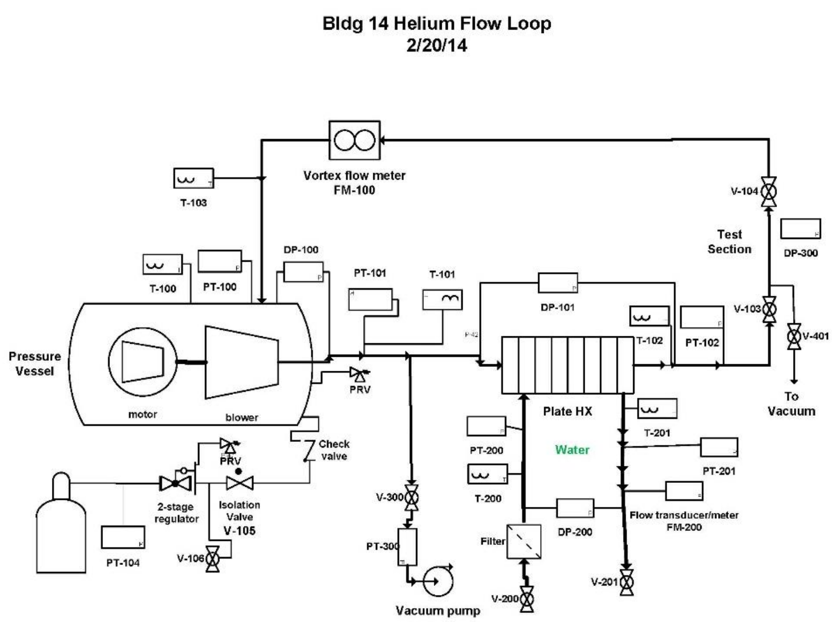

Figure 8. P&ID for the LANL loop.

A number of flow experiments were conducted using this loop. One interesting experiment investigated the use of tapered exits on the target holder to reduce pressure drop so as to increase mass flow rate. Typically, a bull-nosed entrance and diverging exit are used to minimize pressure drop when entering and then exiting a flow restriction. But with multiple exit channels this is not necessarily as effective as with a single channel because the flows from the adjacent channels mix turbulently. Flow visualization of a 10 disk stack was used to examine the exit flows. This is shown in Figure 9. Pressure drop measurements as well as studies of the exiting streams revealed that there is little benefit to this feature. In the end, a bullnose was applied to both ends of the target holder for the sake of symmetry to avoid improper insertion of target into the housing.

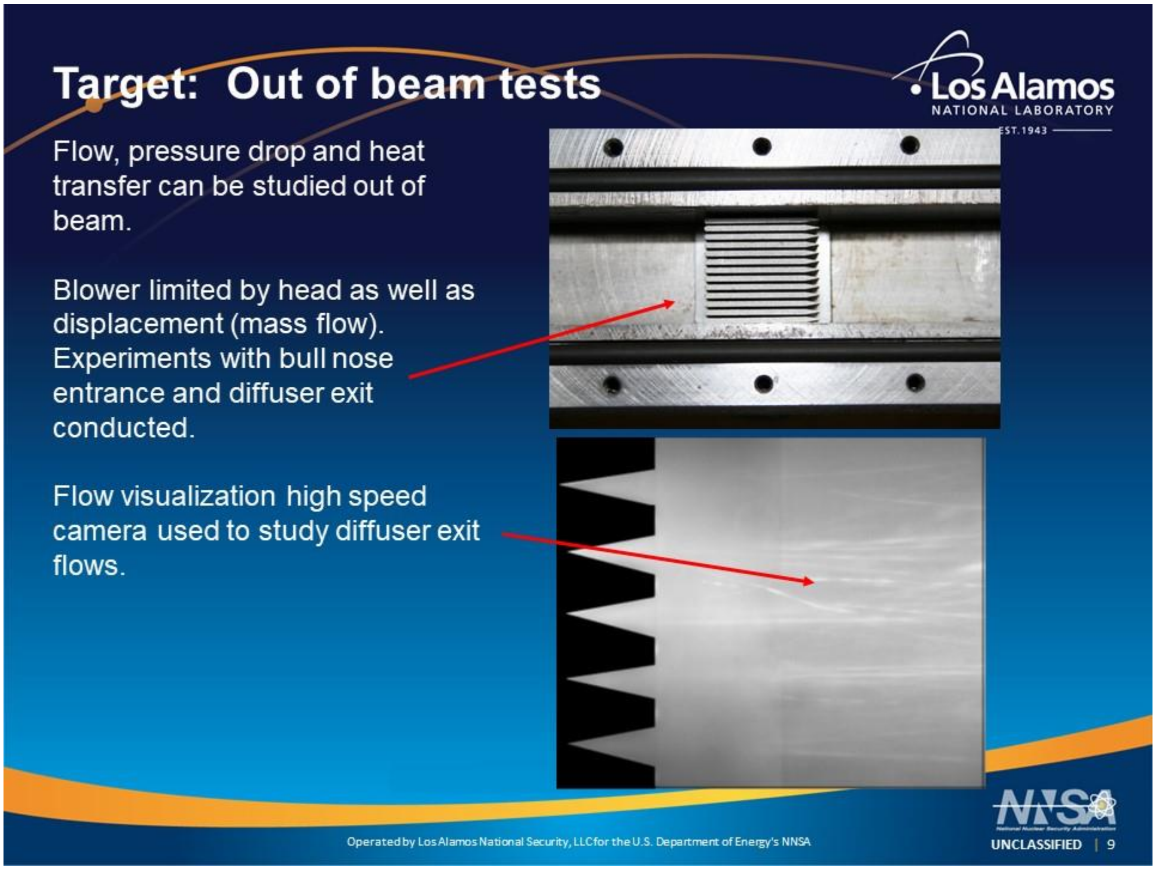

Figure 9. Flow visualization experiments with tapered exit channels on the target holder.

Final Helium Cooling System

By 2015 the target disk diameter had grown to its current 29 mm diameter and at that time there were 82 disks, 0.5 mm think and 0.25 mm coolant gaps between disks. The required mass flow rate has now increased to 300 g/s, requiring a larger blower. Tuthill had no blower capable of meeting this requirement. Aerzen GM 12.4 blower was chosen. This is also pressure vessel mounted (Figure 10). Blower specifications are shown in Figure 11. With this larger displacement machine mass flow up to 400 g/s is possible. Total differential pressure available is 21.76 psi (150 kPa), so the actual flow through the target is limited by the head capacity of the blower, not the mass or volume flow capacity.

This blower performed well but was plagued by seal leaks. The vane drive shaft has oil filled lubricating chambers on both ends. These chambers are sealed with lip seals. The Tuthill blower had breathers on these chambers to prevent pressure build-up but this was lacking on the Aerzen blower. With 300 psi in the pressure vessel and 320 psi inside the blower, the oil chamber would come to that pressure through the lip seals. But when the system was brought back down to 0 gauge pressure the 300 psi in the oil chamber would damage the lip seals. The blower had to be rebuilt and a breather system developed for the blower to operate successfully under pressurized conditions. Breather tubes were connected to the oil fill plugs and vented through a filter (Figure 12). A check valve prevented back flow.

Figure 10. Aerzen blower mounted in a pressure vessel.

AERZEN

Aerzen USA Corporation Quotation nº: PG-130

09/26/2013

Aerzen Rotary Lobe Blower

Performance data:

		GM 13.6	GM 13.6	GM 12.4	GM 12.4
medium		Helium	Helium	Helium	Helium
operating case		Given	Current dP	Given	Current dP
MW	lb/lbM	4.00	4.00	4.00	4.00
K = Cp/Cv	./.	1.660	1.660	1.660	1.660
volumetric flow at intake conditions	icfm	180	150	180	150
volumetric flow at standard conditions	MMscfd	7.225	6.021	7.225	6.021
volumetric flow at standard conditions	scfm	5,017	4,181	5,017	4,181
specific weight at intake conditions	lb/ft³	0.294	0.294	0.294	0.294
intake pressure (absolute)	psia	414.5	414.50	414.50	414.50
discharge pressure (absolute)	psia	436.3	432.50	436.25	432.50
differential pressure	psi	21.8	18.0	21.8	18.0
intake temperature	°F	66.2	66.2	66.2	66.2
discharge temperature	°F	83	81	81	79
blower speed	rpm	1,019	877	1,737	1,482
motor speed	rpm	1,019	877	1,737	1,482
power required at blower shaft	BHP	28	20	24	18
motor rating	HP	40	25	30	20

Figure 11. Aerzen blower specifications.

Figure 12. Lubrication chamber breathing system

Blower performance measurements were taken to establish the mass flow rate as a function of the closed loop pressure drop. Pressure drop and flow rate were varied using a throttle valve.

Measurements were made at 4 motor rpm. The results are shown in Figure 13 along with the system P&ID. From the test data it is clear that the blower can generate higher differential pressure than predicted by Aerzen, 180 kPa as opposed to 150 kPa.

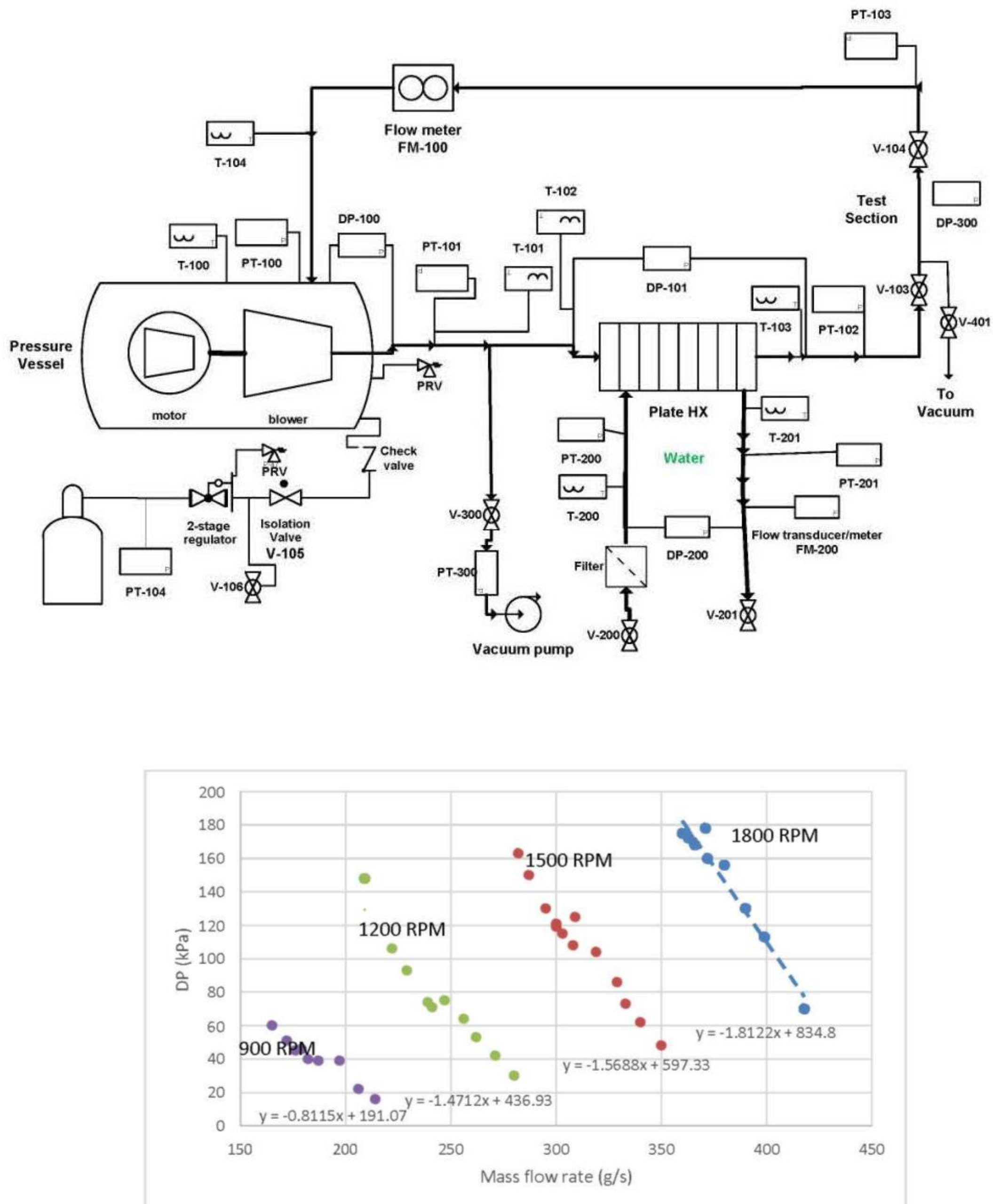

Figure 13. Aerzen blower P&ID and performance test results.

A series of 1000 hr performance tests were conducted to examine performance in plant production operating conditions. This work was reported in detail and will not be reproduced here (Ref 2). The tests were interrupted every 6 days to simulate the expected Mo99 production schedule of 6 days on, 1 day off.

Blower Performance in Cooling the Final Target Design

Northstar has purchased a stand-alone blower that does not require enclosure in a pressure vessel. This is the superior system choice if funds are sufficient, and probably less expensive in the long run because of reduced maintenance time and effort. The flow through the target and the quality of the cooling is not unique to the blower, only to the available head and the ability of the blower to deliver the intended mass flow. LANL analysis to date is limited to the target only and does not include bypass flows to cool the housing, the target insertion mechanism or any of the insertion piping.

The design mass flow rate has been 300 g/s for several years. The target disk sizes and spacing changed over the years but the baseline in the recent LANL analysis is 82 disks, 0.5 mm thick and 29 mm in diameter, separated by 0.25 mm gaps for the helium coolant flow. The window is curved, concave into the target and the helium flow, for enhanced cooling while withstanding the helium pressure. The window to first disk gap is 0.5 mm. The beam is 38 MeV and 6.32 mA, 250 kW beam power, about 160 kW_{th} in the target.

At 300 g/s, the average helium velocity is 150 m/s in the cooling channels, with a peak of 400 m/s across the window at center. The pressure drop across the target is only 81 kPa, indicating that higher mass flow rate is possible even with other pressure drops in the closed loop (see Figure 13 above). Temperature profiles in the target and peak temperature bar chart are shown in Figure 14. Window temperature is 513°C, peak disk temperature is nearly 1300°C. The Inconel window strength is sufficient at this temperature but above 700°C the material ultimate tensile strength (UTS) begins to drop steeply.

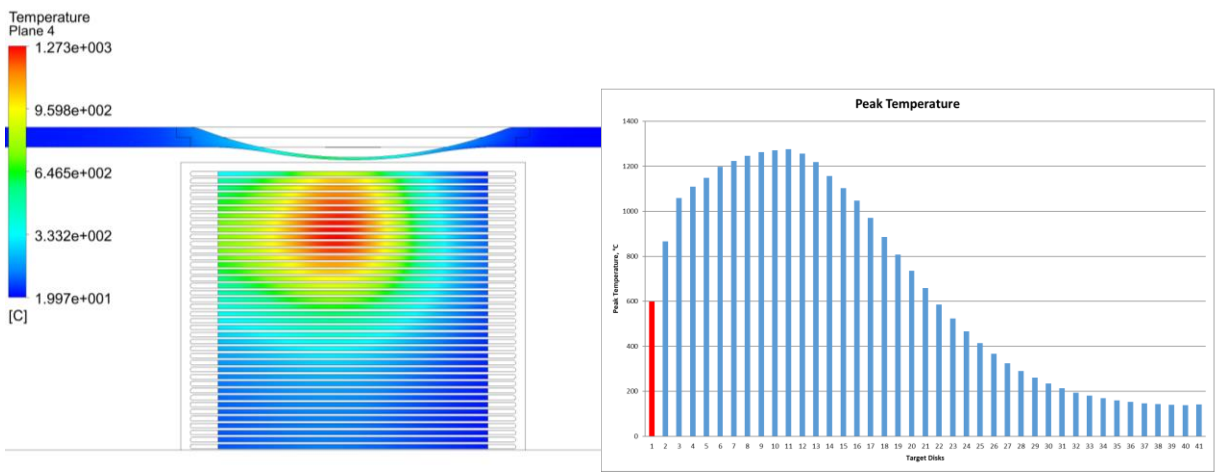

Figure 14. Target temperatures with 300 g/s cooling.

Higher mass flow rate, as far as can be achieved, reduces temperature of the window and the Mo disks. At 400 g/s the average velocity through the channels is 200 m/s and 460 m/s in the window channel. Target pressure drop is 161 kPa, 23.4 psi. Temperature profiles in the target and peak temperature bar chart are shown in Figure 15. Window temperature is 400°C, peak disk temperature is just over 1000°C.

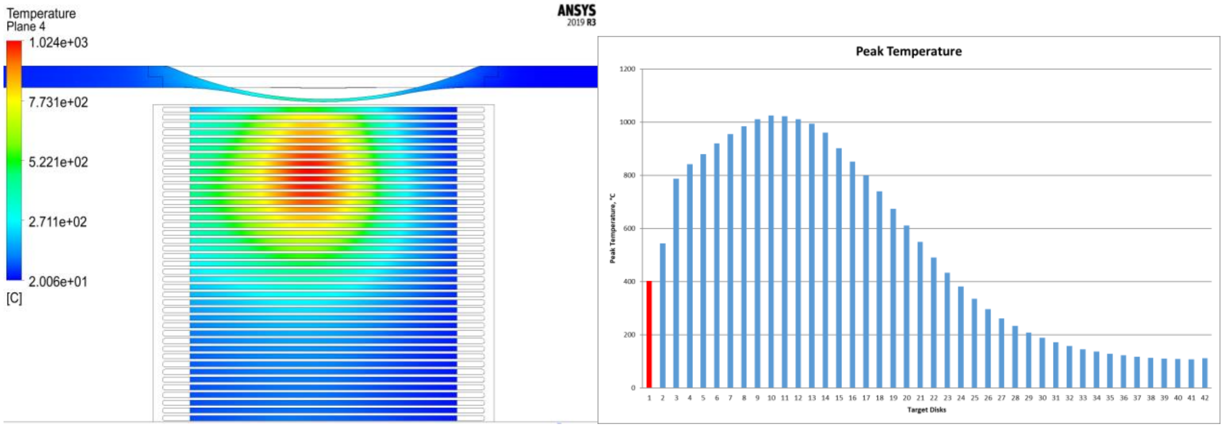

Figure 15. Target temperatures with 400 g/s helium flow.

The goal of 500 g/s through the target seems out of reach. Pressure drop is calculated to be 240 kPa (34.8 psi), beyond the capacity of the blower. This would reduce the peak disk temperature to 840°C and window temperature to 365°C, with average velocity through the target of 250 m/s and 590 m/s across the window. Calculated performance predictions for 300, 400 and 500 g/s are summarized in Table 1. Calculated values of velocity between the disks by Argonne National Lab are included in the table. These values are slightly lower, but in the ANL analysis some bypass flows are included, so the total mass flow is not all through the target, hence the lower values.

Table 1. Summary of calculated target cooling at different helium flow rates.

Mass Flow Rate (g/s)	300	400	500
Target Pressure Drop (kPa (psi))	81 (11.8)	161 (23.4)	240 (34.8)
Peak Window Temp (°C)	513	400	365
Peak Disk Temp (°C)	1300	1000	840
Velocity Between Disks (m/s)	150	200	250
ANL Velocity Between Disks (m/s)	141	182	223
Velocity Peak at Window (m/s)	400	542	590

The Northstar stand-alone blower can produce 29 psi but other pressure drops in the system limit pressure drop available to the target to 21 or 22 psi. In that case, 400 g/s is an achievable goal and will be assumed to be the new baseline for further testing and analysis.

Comments and Conclusions

The helium cooling system at the design flow rate of 300 g/s adequately cools the target. All indications are that higher mass flow rate, up to 400 g/s, can be achieved, resulting in lower disk and window temperatures.

Various bypass flows are incorporated into the design. 15 g/s will be directed up the target insertion channel to cool those parts and components. Additional bypass flow is intended for the housing bottom plate. This is accomplished by allowing a 0.5 mm space between the target holder and housing. Test of the flow rate through this channel are currently being readied, as well as flow tests through a full target assembly to confirm the mass flow rate vs pressure drop calculations.

Tests on heated disks are showing considerable distortion due to thermal expansion and possibly stress relief (Ref 3). These distortions are comparable to and sometimes exceeding the disk to disk spacing of 0.25 mm. Some analysis of missing disks and blocked channels was done some years ago showing no major impact, but these studies were very limited in scope. With all or nearly all disks deforming to some extent one can expect some gaps opening wider and some being choked to one degree or another. With a wide margin on disk temperatures to molybdenum melt temperature it is reasonable to assume this is a tolerable situation. The exception may be the first disk, which may move away or toward the window, changing that critical coolant behavior. Window cooling tests with wider gap and with disk touching the window indicate that these conditions can be survived. Protecting the window is the highest priority however, so any possibility of disruption of that cooling channel needs careful consideration. A first disk made of beryllium has been suggested. This disk would experience negligible heating and should be quite robust in that location.

References

1. M. Kalish, et. al. "Design of the NSTX Heating and Cooling System"
2. A. Wass, et. al. "Production Facility Prototype Blower 1000 Hour Test Results II," LANL report LA-UR-18-20146, 12/22/2017. Other related reports: LA-UR-16-27971, LA-UR-18-29897, LA-UR-19-31253 and LA-UR-21-28515.
3. A. Wass, et. al. "Mo100 Disk Structural Integrity Tests I," LA-UR-22-20323, 01/13/2022